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ANALYSIS OF DYNAMIC CHARACTERISTICS OF THE ACTIVE FILTER-STABILIZER

Y. Shcherbak
Doctor of Technical Sciences, Professor, Head of Department
Department of electric transport
O. M. Beketov National University of Urban Economy in Kharkiv
Marshala Bazhanova str., 17, Kharkiv, Ukraine, 61002
E-mail: sherbak47@mail.ru

Yu. Semenenko
Assistant*
E-mail: slider2012@i.ua

A. Semenenko
PhD, Associate Professor*
E-mail: semenoi@i.ua

*Department of electricity, electrical and electromechanical
Ukrainian State University of Railway Transport
Feierbakha sq., 7, Kharkiv, Ukraine, 61050

Для забезпечення ефективної фільтрації і стабілізації напруги тягових підстанцій постійного струму запропоновано застосовувати активні фільтри-стабілізатори. Встановлено, що його перетворювач напруги з двосторонньою широтно-імпульсною модуляцією для малих значень приросту сигналу управління являє собою амплітудно-імпульсний модулятор другого роду. Передача інформації модулятором здійснюється двома каналами, що містять статичний і динамічний коефіцієнти передачі. Одержана імпульсна модель для дослідження динамічних процесів

Ключові слова: активний фільтр-стабілізатор, перетворювальний агрегат, тягова підстанція, широтно-імпульсна модуляція, імпульсна модель

Для обеспечения эффективной фильтрации и стабилизации напряжения тяговых подстанций постоянного тока предложено применять активные фильтры-стабилизаторы. Установлено, что его преобразователь напряжения с двухсторонней широтно-импульсной модуляцией для малых значений приращения сигнала управления представляет собой амплитудно-импульсный модулятор второго рода. Передача информации модулятором осуществляется двумя каналами, содержащими статический и динамический коэффициенты передачи. Получена импульсная модель для исследования динамических процессов

Ключевые слова: активный фильтр-стабилизатор, преобразовательный агрегат, тяговая подстанция, широтно-импульсная модуляция, импульсная модель

1. Introduction

One of the methods for improving electromagnetic compatibility of DC traction system with adjacent electrical installations and high-quality power supply of the electric rolling stock is the application of active voltage filtration and stabilization at the substation output. This is especially true for railways sections with an intensive and high-speed traffic where traditional filtering and regulating devices of traction substations do not meet requirements to the electrical power quality.

2. Literature review and problem statement

To improve quality of electrical power and electromagnetic compatibility of the DC traction power-supply system with adjacent electrical installations, hybrid active filters were developed [1]. Their use in traction substations is not sufficiently effective at high loads since the output voltage of converter units is significantly reduced under such conditions.

Emergence of high-speed keys with IGCT and IGBT has opened up the possibility of creating more efficient systems [2] providing stabilization and active filtering of the traction substation output voltage. In work [3], availability of using for this purpose booster converters based on thyristor rectifiers and rectifiers with pulse-width modulation (PWM) was shown. Due to the higher modulation frequency, the latter provide higher quality of the output voltage from the converter units [4] but their complexity and high cost restrain their use.

To cope with this shortcoming, the results of studies of active filter-stabilizers (AFS) for alternating voltage were considered [5]. They were designed to stabilize voltage in the buses of non-linear consumers and actively filter currents of higher harmonics in alternating voltage networks. The operating principle of the alternating voltage AFS is based on the use of the energy stored in reactive storage units [6].

Based on the analysis of the above solutions, a constant-voltage AFS is proposed that uses the energy of a capacitive storage device to stabilize and actively filter the rectified voltage [7]. The advantage of the BC voltage AFS in comparison with the booster converters based on rectifiers with PWM consists in lessening the number of power switches and losses in energy conversion. Because the study of the proposed AFS was limited to the study of electromagnetic processes, a problem of examining its properties arises as it is an element of automatic control systems.

3. Objective and task of the study

The objective of present study is the examination of the possibility of using AFS as a part of a converter unit for traction substations to actively filtrate and stabilize the rectified voltage.

To achieve this objective, the following tasks must be accomplished:

– to obtain a generalized equivalent circuit of the AFS voltage converter with PWM based on the analysis of its operation modes;

– to perform analysis of dynamic characteristics of the AFS converter using a two-way PWM;

– to obtain a pulse model of the AFS voltage converter with a two-way PWM.

4. Materials and methods used in studying the dynamic characteristics of the active filter-stabilizer

4. 1. Operating modes of the active filter-stabilizer

The AFS circuit based on a capacitive energy storage unit is shown in Fig. 1. As follows from this circuit, the AFS is connected in series with the uncontrolled rectifier unit (RU) of the traction substation. The power part of the AFS is built as a single-phase bridge switch consisting of two controlled keys: VS, VT (based on IGCT and IGBT) and two noncontrolled keys: VD1, VD2. The transformer T_{CR} and the rectifier CR provide charge for the capacitive energy storage unit C_s feeding the AFS switch with DC voltage of the order of 500 V. The control system (CS) with other circuit elements forms a closed-loop automatic control system implementing active filtration and stabilization of the traction substation output voltage u_{out}.

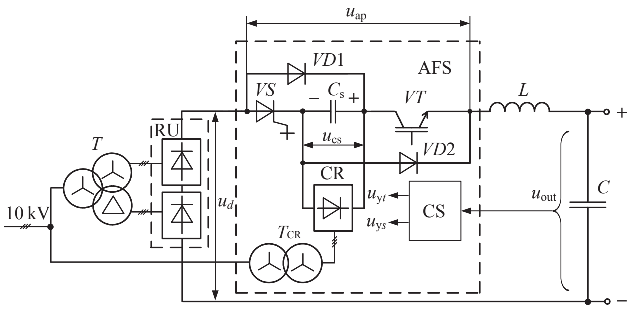


Fig. 1. Circuit of the active filter-stabilizer as a part of the traction substation converter unit

The AFS bridge switch forms pulse voltage u_{ap} from voltage u_{cs} as shown in Fig. 2. A set of values averaged over the PWM period is singled out from voltage u_{ap} by passive LC-filter: a smooth component of the pulse voltage u_{as} is shown by the dashed line in Fig. 2.

Voltage u_{as} contains an alternating component formed to compensate for pulsations of the rectified voltage. In addition, voltage u_{ap} has a constant component U_{a0} formed to stabilize voltage at the output of the converter unit [7]. This is realized by compensating the deviations and oscillations of the constant component of the traction substation output voltage $U_{в0}$ with respect to the specified (nominal) value.

As seen from Fig. 2, the width and the number of pulses of negative polarity decrease when U_{out0} increases. These pulses will disappear when the voltage U_{a0} reaches the value of the negative half-wave amplitude of the variable component U_{avmn}. Thus, when $U_{a0}<U_{avmn}$, the AFS switch forms voltage u_{ap} of a variable polarity like a voltage inverter. At $U_{a0}\geq U_{avmn}$, the switch works as a pulse-width converter with an output unipolar pulse voltage, so it can be simply called a voltage converter.

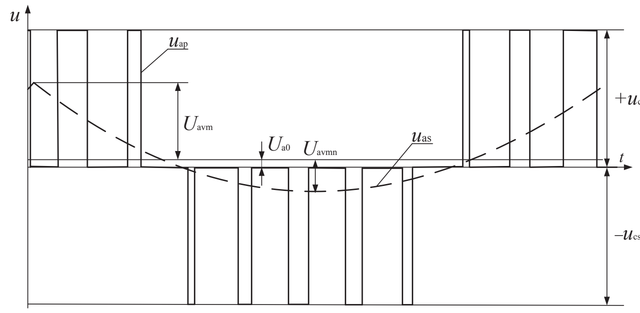


Fig. 2. Diagram of the AFS output voltage

4. 2. Analysis of dynamic characteristics of the active filter-stabilizer

A generalized equivalent circuit of the voltage converter of the active filter-stabilizer with PWM is shown in Fig. 3.

When analyzing dynamic characteristics, the following assumptions are taken: the capacitive energy storage, the control system and the switches of the AFS converter are ideal.

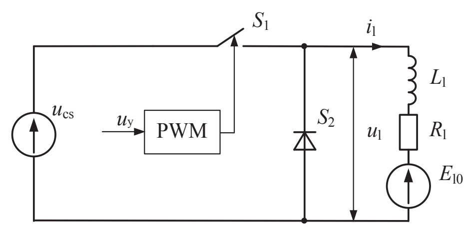


Fig. 3. Generalized equivalent circuit of the voltage converter of the active filter-stabilizer with pulse-width modulation

The time diagrams of the voltages acting in the AFS converter with a two-sided PWM are shown in Fig. 4. The following symbols are used in the time diagrams of the AFS converter voltages:

U_{cs0} is a constant component of the energy storage unit voltage u_{cs};

U_{csvm} is the amplitude of voltage u_{cs} pulsations;

θ_c is the period of discreteness of the accumulator voltage u_{cs} pulsations;

θ_w is the period of the AFS converter's PWM discreteness;

$c=\theta_c/\theta_w$ is the ratio of discreteness periods;

i=1, 2, 3,...c is the sequence number of the PWM discreteness period;

$\theta_{\gamma i}=\gamma_i\,\theta_w$ is duration of the PWM output pulse;

$\Delta\theta_{\gamma is}$ and $\Delta\theta_{\gamma ie}$ are increments in the duration of the PWM output pulse;

u_{pis} and u_{pie} are sequences of the pulses containing information on the increment of the output AFS voltage pulse.

It should be noted that the ratio of discreteness periods (c) was chosen from the condition of multiplicity of fundamental frequencies of the accumulator voltage u_{csp} pulsation harmonics and the AFS converter PWM frequency. Otherwise, as a result of interaction of canonical and noncanonical harmonics of the capacitive energy storage unit voltage with the own harmonics of the AFS converter, generation of low-frequency harmonics occurs into the output voltage [8, 9]. As a result of their electromagnetic effect, malfunctions and failures in the work of railway communication, signaling, centralization and automatic locking can occur. Also, the pulsation coefficient of the converter unit output voltage increases significantly which worsens electromagnetic compatibility of the traction substation with the load. The low-frequency harmonics getting into the passband of the AFS converter frequency characteristic complicate dynamic processes in a closed-loop automatic control system with a possible loss of stability.

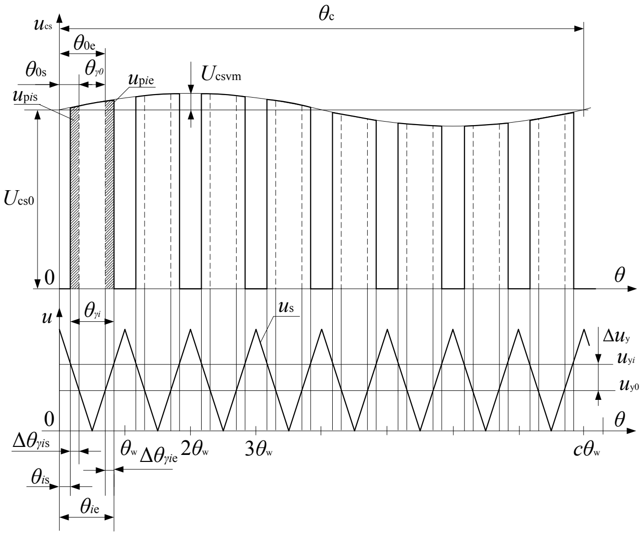


Fig. 4. Voltage diagrams in the AFS converter with a two-way PWM in a dynamic mode

To analyze dynamic characteristics of the AFS voltage converter with a two-sided PWM in accordance with work [9], give a small increment Δu_y to the control signal u_y. The increment in the AFS converter output signal Δu_l resulted from the increment in the input signal Δu_y in the structural loop of automatic regulation is determined relative to the control signal u_y by the following transcendental equation:

$$\Delta u_{н}[\Delta u_y(\theta_{is};\theta_{ie})] = u_{н}(u_{y0}+\Delta u_y) - u_{п}(u_{y0}). \quad (1)$$

The increment in the AFS converter output signal Δu_l is represented in the time voltages diagrams (Fig. 4) as two periodically repeating sequences of pulses u_{pis} and u_{pie} with durations $\Delta\theta_{\gamma is}$ and $\Delta\theta_{\gamma ie}$. In dynamic mode at infinitesimal increments of the control signal Δu_y, the pulse sequences u_{pis} and u_{pie} contain information on the increments of the output signal of the AFS converter with an amplitude equal to the sum of constant and pulsating voltage components. The value of the accumulator voltage pulsating component is determined by:

$$u_{csp}(\theta) = \sum_{v=2}^{\infty} U_{csvm}\sin(v\theta+\varphi_v) + \sum_{k=m}^{\infty} U_{cskm}\sin(k\theta+\varphi_k), \quad (2)$$

where U_{csvm} and U_{cskm} are the amplitudes of the v-th non-canonical and k-th canonical harmonics of voltage u_{csp}; ϕ_v and ϕ_k are the angles of shift of the corresponding voltage harmonics.

Linearize equation (1) to determine dynamic relationship between the increments of the input and output quantities (Δu_y and Δu_l) relative to the system state at a new value of signal u_{yi}. Decompose equation (1) into the generalized Taylor series and confine by linear terms [9] to obtain:

$$\Delta u_l = \frac{Du_l(\theta_{is})}{du_y}\cdot\frac{\Delta u_y}{1!} + \frac{Du_l(\theta_{ie})}{du_y}\cdot\frac{\Delta u_y}{1!}, \quad (3)$$

where D denotes operation of generalized differentiation.

The generalized derivative of the function having discontinuity of the first kind and depending on the parameter is determined according to [10] as follows:

$$\frac{Du_l(\theta_i)}{du_y} = \frac{\partial u_l(\theta_i)}{\partial u_y(\theta_i)} - \Delta u_{pi}\frac{d\theta_i}{du_y}\delta(\theta_{\gamma i}-\theta_i). \quad (4)$$

Since the output signal of the AFS converter in the interval of the PWM pulse action is invariant to changes in the regulated parameter γ_i, then

$$\frac{\partial u_l(\theta_i)}{\partial u_y(\theta_i)} = 0 \quad (5)$$

in equation (4).

The jumps of the output voltage at the break points of each interval of the PWM discreteness are determined by the sum of the smooth and pulsating components of the pulse sequences u_{pis} and u_{pie}:

$$\Delta u_{pis} = U_{cs0} + \sum_{v=2}^{\infty} U_{\text{cнvm}}\sin(v\theta_{is}+\varphi_v) +$$

$$+\sum_{k=m}^{\infty} U_{cskm}\sin(k\theta_{is}+\varphi_k); \quad (6)$$

$$\Delta u_{pie} = U_{cs0} + \sum_{v=2}^{\infty} U_{csvm}\sin(v\theta_{ie}+\varphi_v) +$$

$$+\sum_{k=m}^{\infty} U_{cskm}\sin(k\theta_{ie}+\varphi_k). \quad (7)$$

Equation (3) with allowance for equations (4)–(7) for the n-th interval of discreteness of the converter feed voltage pulsation takes the form:

$$\Delta u_l = -\frac{\Delta u_y(\theta_{is})}{1!}\times$$

$$\times\left[U_{cs0} + \sum_{v=2}^{\infty} U_{csvm}\sin(v\theta_{is}+\varphi_v) + \sum_{k=m}^{\infty} U_{cskm}\sin(k\theta_{is}+\varphi_k)\right]\frac{d\theta_{is}}{du_y}\times$$

$$\times\sum_{i=1}^{c}\delta(\theta_{\gamma i}-\theta_{is}) - \frac{\Delta u_y(\theta_{ie})}{1!}\times$$

$$\times\left[U_{cs0} + \sum_{v=2}^{\infty} U_{csvm}\sin(v\theta_{ie}+\varphi_v) + \sum_{k=m}^{\infty} U_{cskm}\sin(k\theta_{ie}+\varphi_k)\right]\frac{d\theta_{ie}}{du_y}\times$$

$$\times\sum_{i=1}^{c}\delta(\theta_{\gamma i}-\theta_{ie}). \quad (8)$$

For the structural loop of automatic regulation containing a converter with a two-way PWM, the conditions of switching with respect to the initial system state (Fig. 4) for the first and the second meeting points have the following form:

$$u_y(\theta_{0s}+\Delta\theta_{\gamma is}) = u_s(\theta_{is}); \quad (9)$$

$$u_y(\theta_{0e}+\Delta\theta_{\gamma ie})=u_s(\theta_{ie}). \quad (10)$$

For small increments $\Delta\theta_{\gamma is}$ and $\Delta\theta_{\gamma ie}$ in the transducer output pulse duration, the transcendental equations (9) and (10) can be approximated relative to the initial system state with the first two terms of the Taylor series. In this case, the left and right sides of equations (9) and (10) respectively take the following form for the meeting points:

$$u_y(\theta_{0s}+\Delta\theta_{\gamma is})=u_y(\theta_{0s})+\Delta u_y(\theta_{0s})+\frac{du_y(\theta_{0s})}{d\theta}\Delta\theta_{\gamma is};$$

$$u_s(\theta_{is})=u_s(\theta_{0s})+\frac{du_s(\theta_{0s})}{d\theta}\Delta\theta_{\gamma is}; \quad (11)$$

$$u_y(\theta_{0e}+\Delta\theta_{\gamma ie})=u_y(\theta_{0e})+\Delta u_y(\theta_{0e})+\frac{du_y(\theta_{0e})}{d\theta}\Delta\theta_{\gamma ie};$$

$$u_s(\theta_{ik})=u_s(\theta_{0e})+\frac{du_s(\theta_{0e})}{d\theta}\Delta\theta_{\gamma ie}. \quad (12)$$

The control signal of the AFS converter in the structural loop of automatic regulation contains two components:

$$u_y(\theta)=u_{y0}(\theta)+u_{yp}(\theta), \quad (13)$$

where $u_{y0}(\theta)$ is the component representing the reference signal proportional to the mean value of the converter output voltage; $u_{yp}(\theta)$ is the component proportional to the pulsating component of the output voltage of the AFS converter with PWM which falls on the input of its control system by the feedback circuit.

Take into account equation (13) and substitute equations (11), (12) into equations (9) and (10) to obtain equations for the first and second meeting points:

$$u_{y0}(\theta_{0s})+\Delta u_{y0}(\theta_{0s})+\frac{du_{y0}(\theta_{0s})}{d\theta}\Delta\theta_{\gamma is}+u_{yp}(\theta_{0s})+$$
$$+\frac{du_{yp}(\theta_{0s})}{d\theta}\Delta\theta_{\gamma is}=u_s(\theta_{0s})+\frac{du_s(\theta_{0s})}{d\theta}\Delta\theta_{\gamma is}; \quad (14)$$

$$u_{y0}(\theta_{0e})+\Delta u_{y0}(\theta_{0e})+\frac{du_{y0}(\theta_{0e})}{d\theta}\Delta\theta_{\gamma ie}+u_{yp}(\theta_{0e})+$$
$$+\frac{du_{yp}(\theta_{0e})}{d\theta}\Delta\theta_{\gamma ie}=u_s(\theta_{0e})+\frac{du_s(\theta_{0e})}{d\theta}\Delta\theta_{\gamma ie}. \quad (15)$$

Following transformation of equations (14) and (15), equations for determining increments $\Delta\theta_{\gamma is}$ and $\Delta\theta_{\gamma ie}$ in duration of the PWM output pulse can be obtained. The following are the increments for the meeting points:

$$\Delta\theta_{\gamma is}=\frac{u_{y0}(\theta_{0s})+u_{yp}(\theta_{0s})+\Delta u_{y0}(\theta_{0s})-u_p(\theta_{0s})}{\frac{du_p(\theta_{0s})}{d\theta}-\frac{du_{y0}(\theta_{0s})}{d\theta}-\frac{du_{yp}(\theta_{0s})}{d\theta}}; \quad (16)$$

$$\Delta\theta_{\gamma ie}=\frac{u_{y0}(\theta_{0e})+u_{yp}(\theta_{0e})+\Delta u_{y0}(\theta_{0e})-u_p(\theta_{0e})}{\frac{du_p(\theta_{0e})}{d\theta}-\frac{du_{y0}(\theta_{0e})}{d\theta}-\frac{du_{yp}(\theta_{0e})}{d\theta}}. \quad (17)$$

For the steady-state of the converter control system with a two-way PWM, the following relationships are valid for the switching moments:

$$u_s(\theta_{is})=u_{y0}(\theta_{is})+u_{yp}(\theta_{is});$$

$$u_s(\theta_{ie})=u_{y0}(\theta_{ie})+u_{yp}(\theta_{ie}). \quad (18)$$

Transform expressions (16), (17) by making passages to the limit in them and taking into account relations (18) and obtain the following for the meeting points:

$$\frac{d\theta_{\gamma is}}{du_{y0}(\theta_{0s})}=$$
$$=\frac{1}{\frac{du_s(\theta_{0s})}{d\theta}-\frac{du_{y0}(\theta_{0s})}{d\theta}-\frac{du_{yp}(\theta_{0s})}{d\theta}}; \quad (19)$$

$$\frac{d\theta_{\gamma ie}}{du_{y0}(\theta_{0e})}=$$
$$=\frac{1}{\frac{du_s(\theta_{0e})}{d\theta}-\frac{du_{y0}(\theta_{0e})}{d\theta}-\frac{du_{yp}(\theta_{0e})}{d\theta}}. \quad (20)$$

The transfer function of the reduced continuous part of the closed-loop automatic system of regulating output coordinates of the converter with PWM has a difference of degrees of denominator and numerator polynomials less than two. This means that the control signal u_y has discontinuities of the first kind at the switching moments θ_{0s} and θ_{0e}. Under these conditions, the derivatives of $u_{y0}(\theta_{0s})$ and u_{y0} (θ_{0e}) in expressions (19), (20) are equal to their left-side values.

Introduce notation of the pulsation factor [11] which, as applied to our problem for both meeting points, is defined as:

$$F_{is}^{-1}=1-\frac{\frac{du_{y0}(\theta_{0s})}{d\theta}}{\frac{du_s(\theta_{0s})}{d\theta}}-\frac{\frac{du_{yp}(\theta_{0s})}{d\theta}}{\frac{du_s(\theta_{0s})}{d\theta}}; \quad (21)$$

$$F_{ie}^{-1}=1-\frac{\frac{du_{y0}(\theta_{0e})}{d\theta}}{\frac{du_s(\theta_{0e})}{d\theta}}-\frac{\frac{du_{yp}(\theta_{0e})}{d\theta}}{\frac{du_s(\theta_{0e})}{d\theta}}. \quad (22)$$

Transform equations (21), (22) taking in account (19), (20) and obtain the following:

$$\frac{d\theta_{\gamma is}}{du_{y0}(\theta_{0s})}=-F_{in}\frac{d\theta}{du_s(\theta_{0s})};$$

$$\frac{d\theta_{\gamma ie}}{du_{y0}(\theta_{0e})}=-F_{ik}\frac{d\theta}{du_p(\theta_{0e})}. \quad (23)$$

Relations (23) enable the equation (8) to be represented in the form:

$$\Delta u_l = \Delta u_y(\theta_{is}) \times$$
$$\times\left[U_{cs0} + \sum_{v=2}^{\infty} U_{csvm}\sin(v\theta_{is}+\varphi_v) + \sum_{k=m}^{\infty} U_{cskm}\sin(k\theta_{is}+\varphi_k)\right]\times$$
$$\times F_{is}\frac{d\theta_{is}}{du_s(\theta_{is})}\times\sum_{i=1}^{c}\delta(\theta_{\gamma i}-\theta_{is}) + \Delta u_y(\theta_{ie})\times$$
$$\times\left[U_{cs0} + \sum_{v=2}^{\infty} U_{csvm}\sin(v\theta_{ie}+\varphi_v) + \sum_{k=m}^{\infty} U_{cskm}\sin(k\theta_{ie}+\varphi_k)\right]\times$$
$$\times F_{ie}\frac{d\theta_{ie}}{du_p(\theta_{ie})}\times\sum_{i=1}^{c}\delta(\theta_{\gamma}-\theta_{ie}). \qquad (24)$$

Equation (24) enables obtaining a dynamic relation between the increments Δu_y and Δu_l of the input the output quantity relative to the system state at a new value of the control signal with consideration of the pulsation factor.

5. The results obtained in the study of dynamic characteristics of the active filter-stabilizer

It follows from equation (24) that the AFS voltage converter with a two-way PWM for small control signal increment values is an amplitude-pulse modulator of the second kind. In it, information is transferred by two channels, each of them having static and dynamic transfer factors. These factors are determined by the type of the sweep signal and the pulsating component of the AFS converter output voltage.

Static transfer factors for the meeting points are respectively equal to:

$$K_{is} = \frac{d\theta_{is}}{du_p(\theta_{is})}\times$$
$$\times\left[U_{cs0} + \sum_{v=2}^{\infty} U_{csvm}\sin(v\theta_{is}+\varphi_v) + \sum_{k=m}^{\infty} U_{cskm}\sin(k\theta_{is}+\varphi_k)\right];$$

$$K_{ie} = \frac{d\theta_{ie}}{du_p(\theta_{ie})}\times$$
$$\times\left[U_{cs0} + \sum_{v=2}^{\infty} U_{csvm}\sin(v\theta_{ie}+\varphi_v) + \sum_{k=m}^{\infty} U_{cskm}\sin(k\theta_{ie}+\varphi_k)\right].$$

Equation (24) has the following form after transformations with consideration of repeatability of the processes at the discreteness intervals θ_c of the voltage converter feed pulsation:

$$\Delta u_l = \Delta u_y(\theta_{is})\theta_w\sum_{n=1}^{\infty}\sum_{i=1}^{c}K_{is}F_{is}\delta(\theta_{\gamma i}-\theta_{is}) +$$
$$+\Delta u_y(\theta_{ie})\theta_w\sum_{n=1}^{\infty}\sum_{i=1}^{c}K_{ie}F_{ie}\delta(\theta_{\gamma i}-\theta_{ie}). \qquad (25)$$

In accordance with equation (25), a pulse model of an AFS converter with a two-way PWM was constructed (Fig. 5).

In the pulse model, two ideal pulse elements have a quantization period equal to the PWM period Tm of the AFS voltage converter. The lower pulse element has a delay in quantizing the input signal by the length of the PWM output pulse $\gamma_i T_m$. The reduced continuous parts contain information on static K_{is}, K_{ie} and dynamic F_{is}, F_{ie} transfer coefficients.

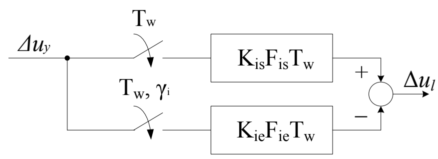
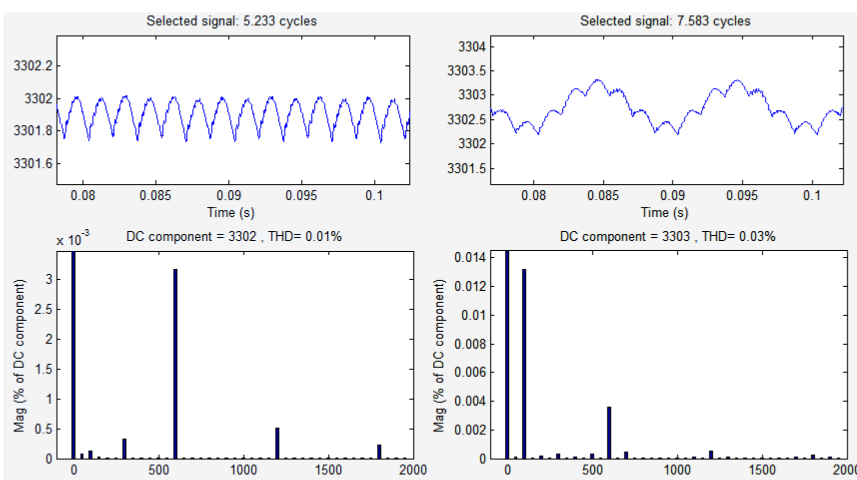


Fig. 5. Pulse model of the voltage converter for an active filter-stabilizer with a two-way pulse width modulation

By analysis of equation (25), it was established that the dynamic connection between the increments of the AFC converter input and output signal (Δu_y and Δu_l) at each interval of the PWM discreteness had a variable character. This property of the converter with a two-way PWM is caused by the changes in static K_{is}, K_{ie} and dynamic F_{is}, F_{ie} transfer coefficients. These features of the converter must be taken into account when describing dynamic processes in a closed-loop automatic control system.

To verify reliability of the results obtained, a Matlab model of the converter unit including an AFS with a two-way PWM was constructed. Simulation was carried out under an active-inductive load, at symmetry and asymmetry of the three-phase feeding voltage ε=2 %. The simulation results are shown in Fig. 6 for load R_l=1 Ohm, L_l=5 mH.



a *b*

Fig. 6. Voltage pulsations and spectral composition diagrams at the output of the converter unit with AFS at symmetry (*a*) and asymmetry (*b*) of three-phase feeding voltage

In this simulation, an equivalent interfering voltage meter developed and proposed in [12] was used. It has demonstrated that the equivalent interfering voltage was equal to U_{em}=0.352 V for the above conditions. The performed verification confirmed the possibility of stabilizing the output voltage in conditions of variation of three-phase voltage within 9.5÷10.5 kV and load within R_l=1÷100 Ohm.

6. Discussion of the results obtained in the study of dynamic characteristics of the active filter-stabilizer

Equation (25) was obtained which establishes dynamic relationship between the of the input and output value increments (Δu_y and Δu_l) relative to the system state at a new value of the control signal taking into account the pulsation factor. Based on this, a pulse model was proposed for its application in further studies of the dynamic processes in the closed-loop structures containing a voltage converter with a two-way PWM. First of all, it is a question of synthesis of the regulator and the possibility of realizing converter unit for the processes of finite duration in closed-loop automatic control systems.

High quality of stabilization and active filtration of the output voltage was confirmed, even at a considerable asymmetry of the three-phase voltage feeding the converter unit. One of the confirming examples was the equivalent interfering voltage which was well below the permissible value of 4 V under conditions of asymmetry of the feed voltage.

7. Conclusions

1. It was shown that the APS voltage converter works in various modes as a voltage inverter or as a pulse-width converter of a reducing type. On the basis of the process analysis, a generalized equivalent circuit of an AFS converter with PWM was proposed.
2. Studies of the dynamic characteristics of the AFS voltage converter with a two-way PWM have been carried out. Based on the performed analysis, it was established that the AFS converter is an amplitude-pulse modulator of the second kind for small control signal increment values. Information is transferred in it by two channels having static and dynamic transfer coefficients.
3. A pulse model of AFS converter with a two-sided PWM was obtained for the study of dynamic processes in closed-loop structures. It contained two ideal pulse elements with a quantization period equal to the PWM period and the continuous part of the model reflects information on the transfer coefficients.

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